SPATIAL VARIABILITY OF DIELECTRIC PROPERTIES IN FIELD SOILS

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ABSTRACT

Most mine detection sensors are affected by soil properties such as water content, temperature, electrical conductivity, and dielectric constant. The most important of these is water content since it directly influences the three other properties. The variability of these properties may be such that either potential landmine signatures are overshadowed or false alarms result. In this paper we present the results of field measurements in the Netherlands, Panama, and New Mexico on spatial variability of soil water content. We also discuss how the variability of soil water content affects the soils electrical conductivity and dielectric constant and the resulting response of a ground penetrating radar system .

Keywords: spatial variability, soil water content, dielectric constant, electrical conductivity, mine detection, climate.

1. INTRODUCTION

Many sensors for landmine detection are affected by the water content, temperature, electrical conductivity and dielectric constant of the surrounding soil. The most important of these is soil water content since it directly influences the three other properties. Hendrickx et al. (1999) and Das et al. (2001) have studied transient soil water content regimes around landmines in six soil textures varying from sandy loam to clay loam under the climatic conditions of humid Bosnia and arid Kuwait. Their results indicate that soil water distributions around landmines can be highly variable in space and time. Borchers et al. (2000) integrated a number of models into a MATLAB software package for the prediction of the dielectric constant, velocity of ground penetrating radar (GPR) signals, attenuation, and reflection coefficient from soil type and soil water content. They used this software package to determine whether or not field conditions are appropriate for use of the GPR. Under dry conditions many soils will have a water content that is too low for good GPR performance but moist and wet soils generally are favorable for mine detection using GPR.

These previous modeling studies all assumed homogeneous soils throughout, i.e. the variability of soil water content is caused only by temporal variability of weather parameters such as precipitation and evaporation or by the effect of the mine on water distribution. However, many field observations have shown that soil water content has its own intrinsic spatial variability due to small differences in hydraulic properties, surface unevenness, vegetation, unstable wetting and macropore flow (e.g. Hendrickx et al. 1990; Hendrickx and Walker 1997; Nielsen et al. 1973; Peck 1983). The objective of this study is to present examples of spatial and temporal variability of soil water content in different soils and climates worldwide and to infer in which manner soil water content variability affects the variability of dielectric soil properties and the performance of a GPR for mine detection.

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2. METHODS AND MATERIALS

In this study we will use three sets of soil water content data obtained under widely different climatic conditions: a water repellent soil in The Netherlands, New Mexico desert soils, and a tropical forest soil in Panama.

Water Repellent Soil in The Netherlands

The field experiment was carried out in the western part of the Netherlands near the village of Ouddorp. Between April 1988 and March 1989, ten 5.5 m long and 0.5 m deep trenches were sampled in a 0.05 ha experimental field. For each transect, 100 samples (diameter 5 cm; height 5 cm; volume 100 cm^3) were collected at depths of 5-10, 15-20, 25-30, 35-40 and 45-50 cm. Over the entire study, a total of 5000 soil samples were collected. Each sample was used to determine volumetric soil water content and degree of actual water repellency. Precipitation and ground water depths in the field were measured weekly. A total precipitation of 645 mm was measured between the first and last sampling campaign. The ground water depth fluctuated between 70 and 155 cm below the soil surface. For more details we refer to Ritsema and Dekker (1994). Soil texture consisted of 97% sand and 3% clay. The organic matter content of the top 5 cm was 8.9%, 5-15 cm around 1%, and below 15 cm around 0.5% (Dekker,1998).

Tropical Forest Soil in Panama

For this study we used gravimetric soil water content measurements taken during the period 1982-2000 in the Lutz catchment (9.7 ha) on the Bacco Colorado Island in Panama. Samples (diameter 2.5 cm; length 10 cm; volume 49 cm^3) were taken at ten stations spread out across the catchment. Each station is a circle of 1 m radius. Two samples were withdrawn at each sation, one from 0-10 cm, a second from 30-40 cm. In order to reduce soil compaction by continual use of a sample site, stations are changed approximately every 3-4 years to sites located nearby with visually similar conditions. Both old and new sites are run concurrently for approximately 4 months to check for significant differences between sites. The watershed receives an average of 2638 mm precipitation per year. The meteorological year is divided into two parts: a pronounced dry season (approximately from mid-December to the end of April), and a wet season (May to mid-December). On average, only 293 mm of rain falls during the dry season. The soils in the watershed are Alfisols with a texture of 40% clay, 35% sand, and 25% silt.

Desert Soils in New Mexico

The volumetric soil water contents were taken in the Sevilleta National Wildlife Refuge in the central Rio Grande Basin, Socorro County, New Mexico. The total area of the Sevilleta is 40,000 ha. Twenty sites were established with each site comprised of 15 sampling locations marked by stakes. The 15 stakes were placed 10 meters apart for a total length of 150 m. Fiftenn samples were collected at each measurement day at each site in the upper 5 cm of soil using metal cylinders with a volume of 100 cm^3. Samples were collected on 8 dates between October 14, 1999, and December 3, 2000. In this study we use data from 18 sites with a coarse to medium grained sand texture. Vegetation on the sites consisted of cactus, creosote, shrub, grass, or a mixture of these vegetation types. The average annual precipitation is around 200 mm while the annual potential evapotranspiration is about 2500 mm. Therefore, the Sevilleta is representative for many arid sites in the world.

Statistical analysis

For each of the sampling locations in The Netherlands, Panama, and New Mexico the mean gravimetric or volumetric water content and the coefficient of variability have been calculated for each measurement day. In addition, the statistical distribution of the data has been determined. For the water repellent soil in the Netherlands sufficient data were available for the calculation of semivariograms to determine the spatial correlation length of soil water content.

Response of Ground Penetrating Radar

One important objective of this paper is to learn more about the spatial variability of dielectric soil properties. For the estimation of these parameters we use the 1995 model of Peplinski, Ulaby, and Dobson (1995). The inputs to this model consist of the volumetric water content θ, the frequency f, the fraction of the sand particles S, the fraction of the clay particles C, the density of the soil particles ρ_s (a typical value is 2.66 g/cm^3), and the bulk density of the soil ρ_b. The application of this

model in a soil context has been demonstrated by Borchers et al. (2000). Since the relationship between soil water content and dielectric constant is linear over a wide range of water contents (Topp et al., 1980) the water content variability is linearly related to the variability of the dielectric constant.

However, the relationships between soil water content variability and variability in the strength of the GPR reflections and attenuation losses are nonlinear. . We have used the data on variability of soil water content from this study together with the GPR model of Borchers et al. (2000) to predict the variability of the GPR response with respect to soil water content. 95% confidence intervals for the radar response are obtained by first finding a 95% confidence interval for the soil water content at each value of the mean soil water content. For example, at 10% mean soil water content, with a 10% coefficient of variation, the 95% confidence interval for the soil water content is 8.04% to 11.96%. Reflection and attenuation losses for all water contents in this range are computed, and the maximum and minimum losses become the upper and lower limits of the 95% confidence interval for the loss.

3. RESULTS AND DISCUSSION

Spatial Variability of Soil Water Content

Figures 1 through 3 present the coefficients of variability of field soil water contents that have been measured at the three locations in The Netherlands, Panama, and New Mexico. The coefficient of variability varies from about 5% to as high as 83% while on most days values from 10 to 30% seem to be typical. The highest coefficients of variability observed in the Netherlands coincided with increased actual field measured water repellency (Ritsema and Dekker, 1994). Since water repellency leads to unstable wetting fronts (e.g. Hendrickx et al., 1993) a high soil water content variability is expected. The coefficient of variability close to 70% observed at a water content of about 37% at depth 0-10 cm in Panama (Figure 1) may also be caused by water repellency. The senior author has observed in February 2001 at the end of the dry season that the surface soil of the Lutz watershed becomes quite water repellent. Since water repellency occurs in surface soil layers all of the world (e.g,. Jaramillo et al., 2000), these high coefficients of variability seem to be the norm rather than the exception.

Figure 4 shows the variation of soil water content with depth in the first transect from the Netherlands. Within each depth range, the soil water contents are approximately normally distributed. Furthermore, the standard deviation increases with mean water content. The coefficient of variability ranges from about 10% to 20%. Note the systematic trends in soil water content with depth. Similar patterns were observed in the other nine transects. In general, we can expect that water content will vary systematically with depth, with random variation within each depth layer. The depth profile of water contents is determined largely by the dynamics of wetting and drying fronts passing through the soil. Thus geostatistical analysis of the variation with depth is not appropriate.

However, geostatistical analysis of the random variation within layers is appropriate. Figure 5 shows an empirical semivariogram for the soil water content in the 5-10 cm layer of the first transect. We would expect to see some spatial correlation of soil water content. The semivariogram shows that the spatial correlation length is 40 cm or less. Similar results were obtained for the other layers within the first transect and for the other nine transects. The spatial correlation lengths ranged from about 10 cm to 50 cm. For this water repellent soil, there is very little spatial correlation, resulting in a highly random distribution of soil water content.

Response of Ground Penetrating Radar

When there is uncertainty in the soil water content, there will also be substantial uncertainty in the strength of GPR reflections, because of varying attenuation losses and because of variations in the strength of the reflection from the landmine. Figure 6 shows 95% confidence intervals for the combined losses due to reflection and attenuation for the Panama soil. The soil water content was assumed to be normally distributed with a coefficient of variation of 10%, 20%, 30% or 40%. Similarly, figure 7 shows 95% confidence intervals for the combined losses for the Netherlands soil. Typical uncertainties in the soil water content can result in huge uncertainties in the losses due to reflection and attenuation. In some cases, the variation in soil water content can result in a difference of 30db in the radar response.

4. CONCLUSIONS

In this paper we have examined soil water content data from the Netherlands, Panama, and New Mexico. We have seen that even within a relatively homogeneous soil, there can be substantial variation in soil water content. Soil water content at different depths is affected in a systematic fashion by wetting and drying fronts. Within layers of constant depth, there is also considerable random variation in soil water content from one location to another. Coefficients of variability ranging from 10% to 40% were observed. For the Netherlands data, we were also able to examine the spatial correlation of soil water content. Typical correlation lengths of 50 cm or less were observed.

These variations in soil water content were translated into variability of the soil dielectric constant and the resulting effects on the response of a ground penetrating radar system. In some cases, variations in soil water content could account for 30 db differences in the strength of a GPR reflection from a land mine.

Designers of GPR sensors for landmine detection need to be aware of the consequences of spatial variability of soil physical properties including soil water content variation and the resulting affects on soil dielectric properties.

ACKNOWLEDGMENT

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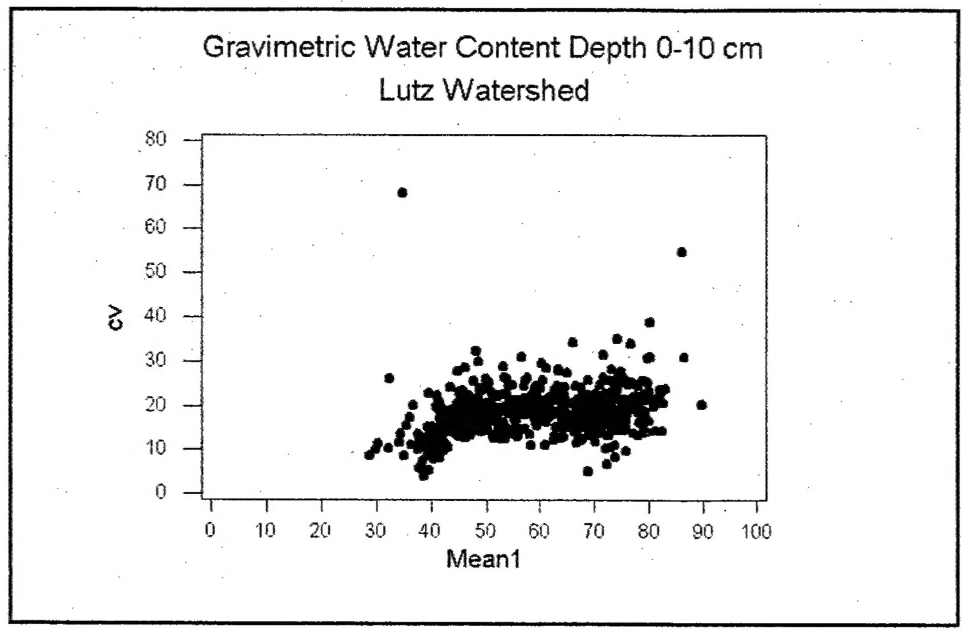
Figure 1. The coefficient of variability versus the mean gravimetric water content at depths 0-10 and 30-40 cm at the Lutz Watershed (Panama) during 1982-2000.



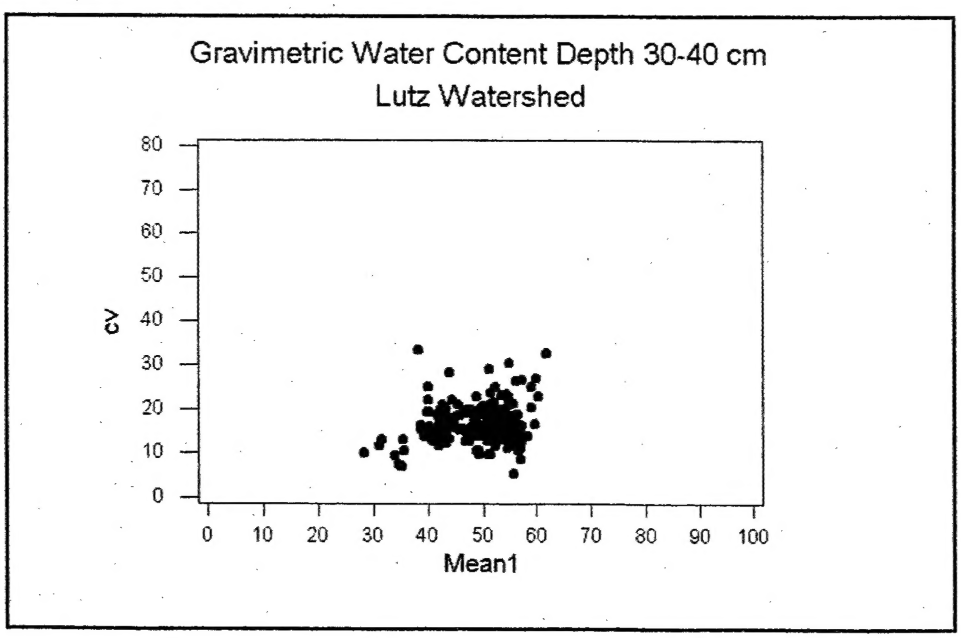


Figure 2. The coefficient of variability versus the mean volumetric water content at depths 5-10, 15-20, 25-30, 35-40, and 40-45 cm in a water repellent soil at Ouddorp (The Netherlands) from April 8, 1988 through February 22, 1989.

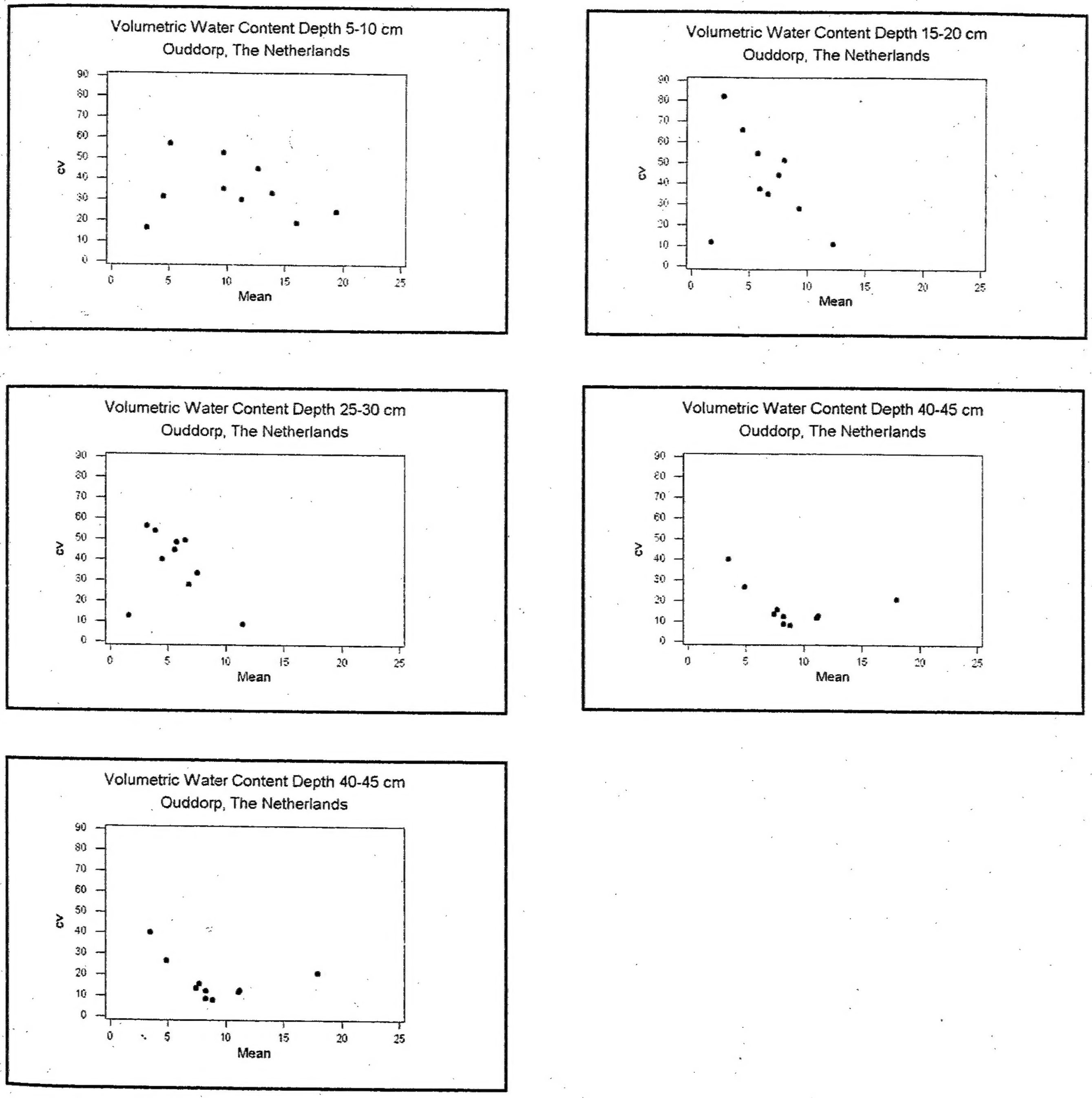


Figure3. The coefficient of variability versus the mean volumetric water content at depth 0-5 cm in the Sevilleta Wildlife Refuge (New Mexico) from October 14, 1999 through December 3, 2000.

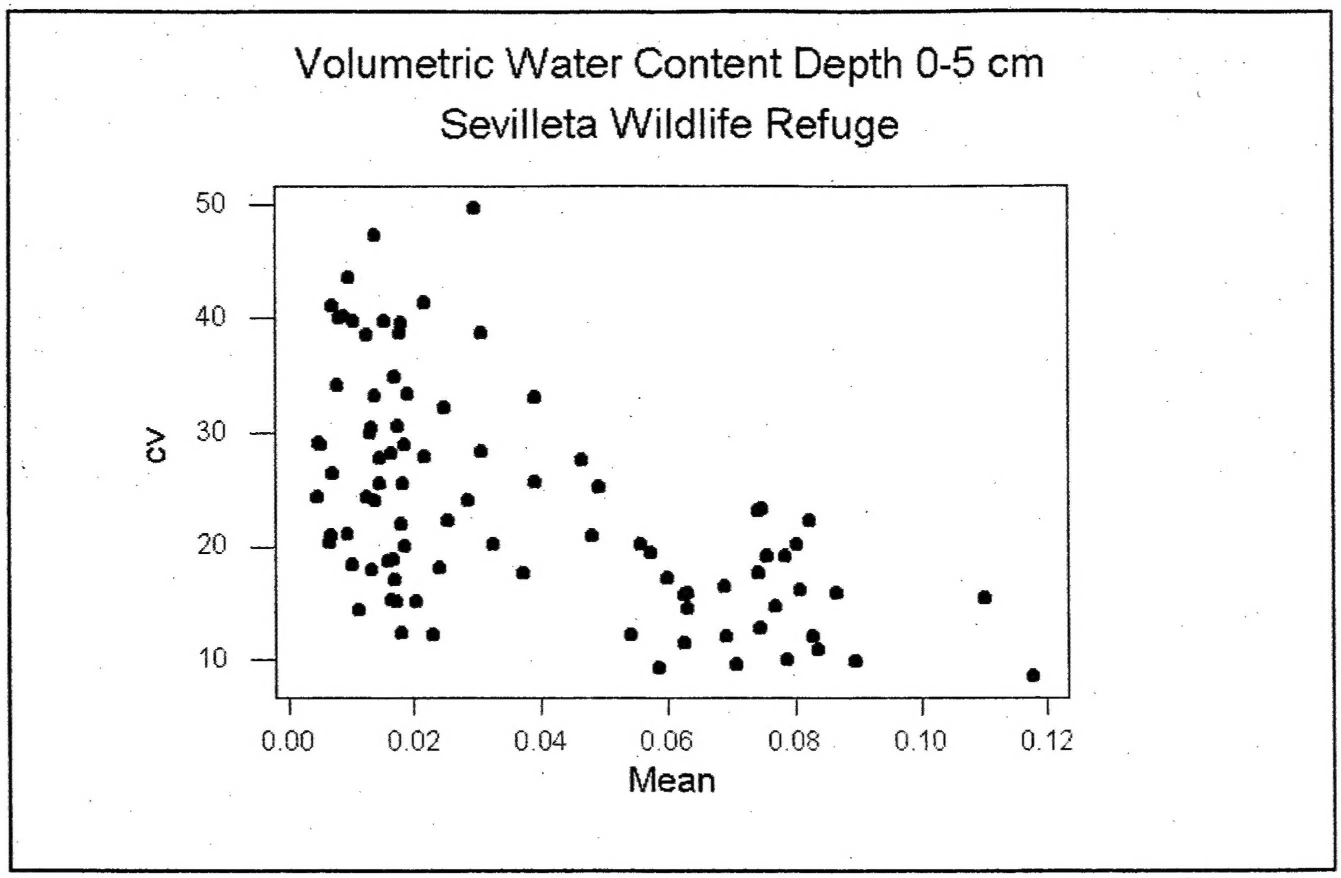


Figure 4. Variation of soil water content with depth from the first Netherlands transect.

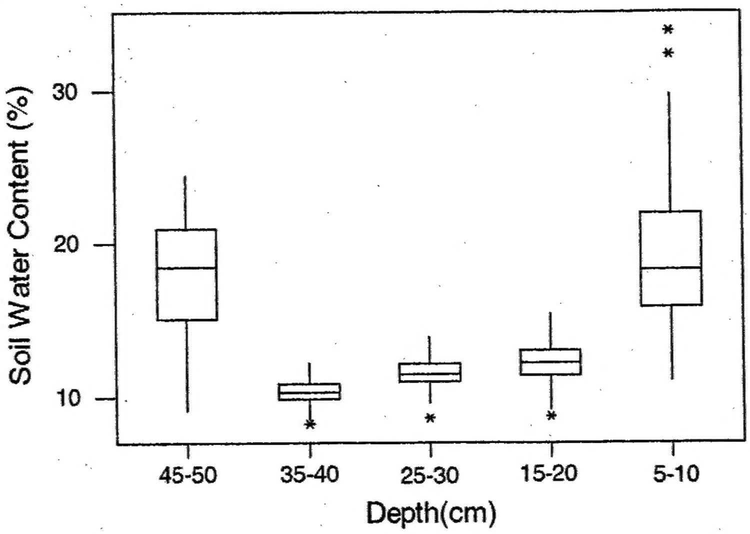
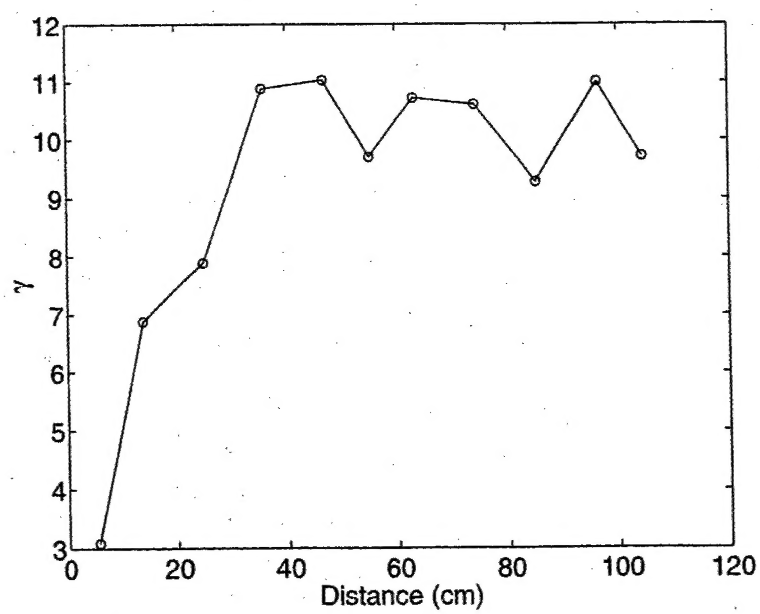
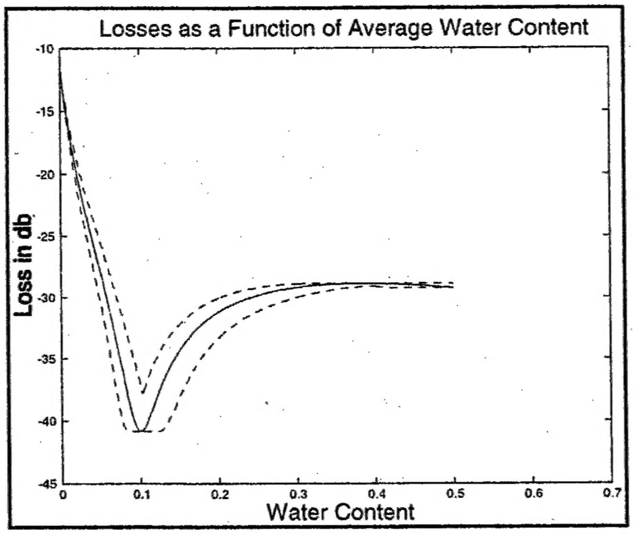


Figure 5. Semivariogram of soil water content for the first layer of the first transect of the Netherlands data.

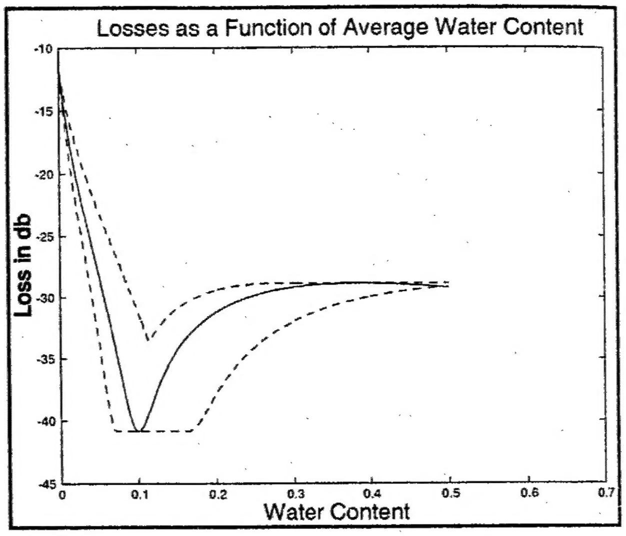


Figuure 6. Predicted losses of the GPR signal in the clay soil of the Lutz Watershed (Panama) as a function of water content and the coefficient of variability of water content.

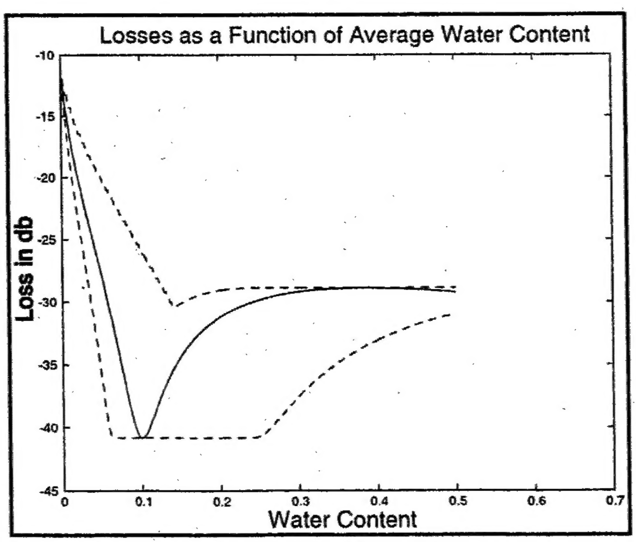
CV = 10 %



CV = 20 %



CV = 30 %



CV = 40 %

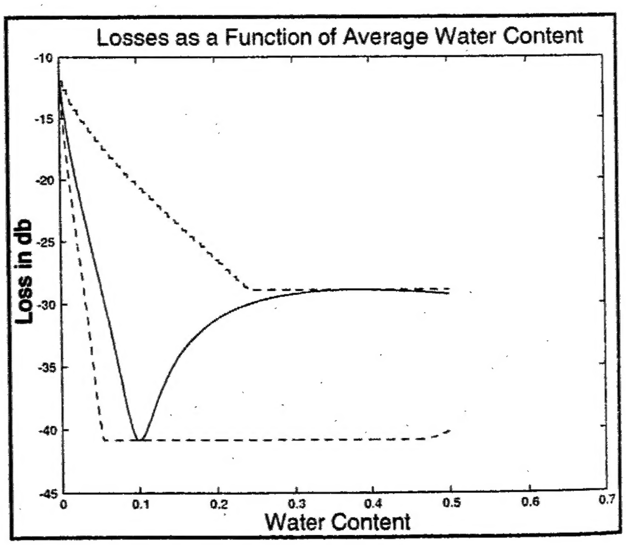
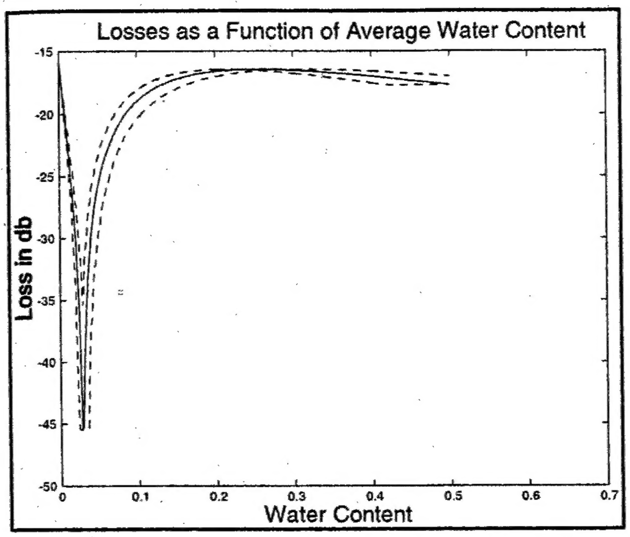
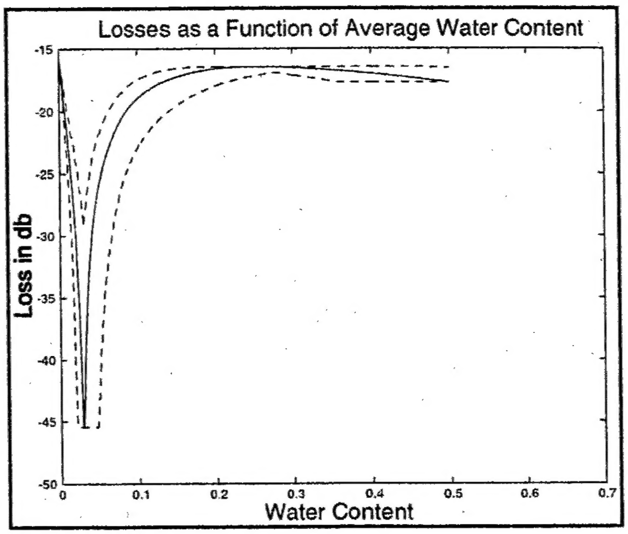


Figure 7. Predicted losses of the GPR signal in the ~~clay~~ SAND soil of ~~the Lutz Watershed (Panama)~~ OUDDERP (NETHERLANDS) as a function of water content and the coefficient of variability of water content.

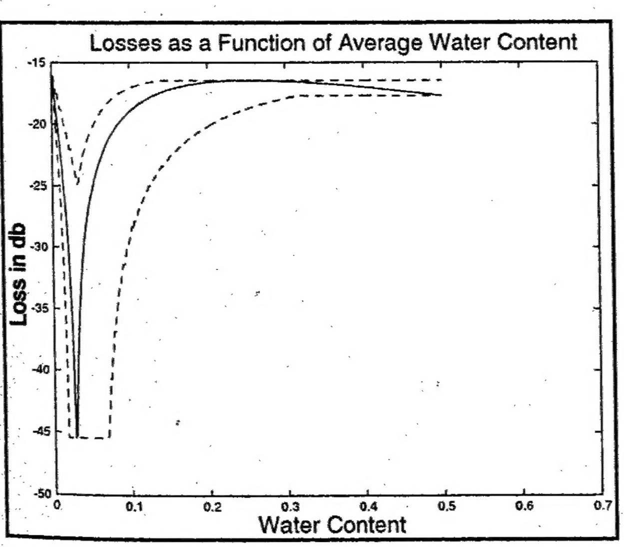
CV = 10 %



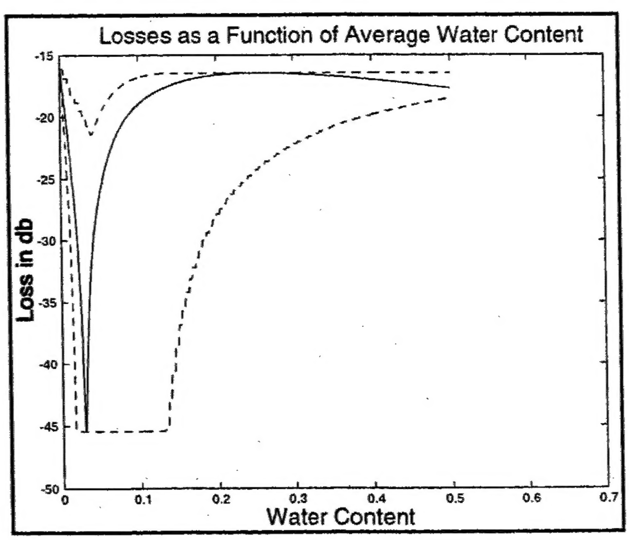
CV = 20 %



CV = 30 %



CV = 40 %



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